15.7 A 2V Organic Complementary Inverter

Stijn De Vusser[1,2], Soeren Steudel[1,2], Kris Myny[1], Jan Genoe[1], Paul Heremans[1,2]

[1]IMEC, Leuven, Belgium
[2]Katholieke Universiteit, Leuven, Belgium

During the last few years, the field of organic electronics has received a great deal of attention as a promising technology for applications requiring low cost, large area coverage, mechanical flexibility, and low temperature processing [1-2]. The performance of Organic Thin-Film Transistors (OTFT's) based on the organic semiconductor pentacene is now at a level comparable to that of amorphous silicon TFT's.

Most of the OTFT-based circuits reported to date use p-type transistors only. However, using a complementary technology leads to lower power dissipation, higher noise margin, better stability and easier design of the circuit. Reduced power dissipation is especially desired for mobile applications. In particular, organic passive radio-frequency identification (RFID) tags will need to draw their power via an RF connection, and the reading distance will be determined by the power required by the tag.

In spite of its clear advantages, there have been only a few attempts for developing a truly organic complementary technology [3, 4]. The reason for this is that the performance and the stability of the n-type organic semiconductors have been problematic. A second issue is the patterning of the n- and p-type semiconductors on the same substrate. As the performance and stability of n-type semiconductors are increasing, a method is proposed here for patterning two small molecule semiconductors on a substrate, leading to a truly complementary organic technology.

An integrated shadow mask is created on top of the OTFT substrate by lithographically patterning a 20μm thick layer of photoresist. A highly doped n++ Si substrate is used, acting both as the substrate and the gate. The process also works using glass substrates and a lithographically patterned metal gate electrode. The gate dielectric is a layer of 100nm SiO_2. Source and drain electrodes consist of 20nm sputtered Au, patterned by optical lithography and lift-off. A schematic cross-section of this device is shown in Fig. 15.7.1

The n- and p-type organic semiconductors are deposited as the last step. The substrate is tilted over +45° during the deposition of the n-type semiconductor copper hexadecafluorophtalocyanine ($F_{16}CuPc$) to create the n-type OTFT's, as shown in Fig. 15.7.2. Subsequently, we tilt the same substrate over -45° during the deposition of the p-type semiconductor pentacene to create the p-type OTFT's (Fig. 15.7.3). Using this method, it is possible to combine any two small molecule n- and p-type semiconductors in a complementary technology. The deposition parameters of both semiconductors can be optimized separately in order to match the n- and p-type transistor parameters as closely as possible.

The superiority of organic complementary technology over a conventional organic p-type-only technology is proven by the fabrication of complementary inverters. Fig. 15.7.4 shows the measured transfer curve of a complementary inverter at a supply voltage V_{DD} of only 2V. The gain of the inverter is substantially higher than 10, even at this extremely low supply voltage. The output voltage swing is 1.96V. The hysteresis is negligibly small. The noise margin of this inverter is more than 0.65V, almost a third of V_{DD}, as calculated by the maximum equal criteria [5]. To the best of our knowledge, these complementary organic devices are the first to feature excellent gain and noise margin at operating voltages significantly smaller than 5V.

Organic passive RFID tags will require a rectifier to produce the supply voltage of the circuit from the received RF carrier. Rectifiers have been fabricated by using vertical organic Schottky diodes, consisting of a stack of Au/pentacene/Al. We have shown experimental operation of this organic diode-based rectifier at frequencies up to 50MHz [6]. However, a rectifier can also be made using an OTFT with its gate shorted to the drain. A planar configuration such as this is easier to integrate with the transistor logic described above. Attempts to achieve 13.56MHz operation with transistor-based rectifiers so far have shown only limited generated DC output voltage [7]. Indeed, the cut-off frequency f_T of a device being (roughly) determined by the square of the distance L over which charge carriers have to travel, f_T is expected to be several orders of magnitude smaller for a typical organic transistor (L = 3μm to 5μm) compared to a vertical Schottky diode (L = 150nm [6]).

However, thanks to its low operating voltage, organic complementary logic may enable the use of transistor-based rectifiers to generate V_{DD}. This has been verified experimentally. The circles in Fig. 15.7.5 are the measured DC voltages generated by a transistor-based diode, with a channel length L of 3μm and width W of 3mm (sufficient to power a load resistor of 50kΩ) in a rectifier with a capacitor of 100nF, powered by an AC signal with 15V amplitude. The solid lines are the calculated achievable DC voltages for such a transistor-based diode, for AC supply voltages of 10V, 15V and 20V. It can be seen both experimentally and theoretically that 13.56MHz is at the edge of operation of a transistor-based diode with channel length of 3μm, but that nevertheless a DC voltage of 2V to 5V, as required by this organic complementary technology, can be produced. Of course, both theory (as shown by the dotted line in Fig. 15.7.5) and experiments (as shown by the square in Fig. 15.7.5) confirm that Schottky-diode based rectifiers have superior performance compared to those based on transistors.

Figures 15.7.6 and 15.7.7 show micrographs of the n- and p-type OTFT's, and of the complementary inverter and a transistor-based diode.

Acknowledgments:
This work is partially supported by the EC-funded Integrated Project POLYAPPLY (IST No. 507143) (http://www.polyapply.org).

References:
[1] W. Clemens et al., "From Polymer Transistors Toward Printed Electronics," *J. Mat. Res.,* vol. 19, pp. 1963-1973, July, 2004.
[2] G. H. Gelinck et al., "Flexible Active-Matrix Displays and Shift Registers Based on Solution-Processed Organic Transistors," *Nat. Mater.,* vol. 3, pp. 106-110, Feb., 2004.
[3] B. Crone et al., "Large-Scale Complementary Integrated Circuits Based on Organic Transistors," *Nature,* vol. 403, pp. 521-523, Feb., 2000.
[4] H. Klauk et al., "Flexible Organic Complementary Circuits," *IEEE Trans. Electron Dev.,* vol. 52, pp. 618-622, Apr., 2005.
[5] J. R. Hauser, "Noise Margin Criteria for Digital Logic Circuits," *IEEE Trans. Educ.,* vol. 36, pp. 363-368, Nov., 1993.
[6] S. Steudel et al., "50 MHz Rectifier Based on an Organic Diode," *Nat. Mater.,* vol. 4, pp. 597-600, Aug., 2005.
[7] R. Rotzoll et al., "13.56 MHz Organic Transistor Based Rectifier Circuits for RFID Tags," *Mater. Res. Soc. Symp. Proc.,* 871E, I11.6, Apr., 2005.

 1-4244-0079-1/06/$20.00 ©2006 IEEE

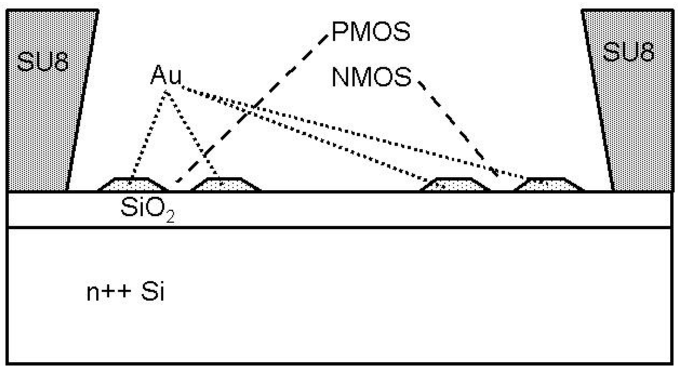

Figure 15.7.1: Schematic cross-section of the complementary device prior to semiconductor deposition.

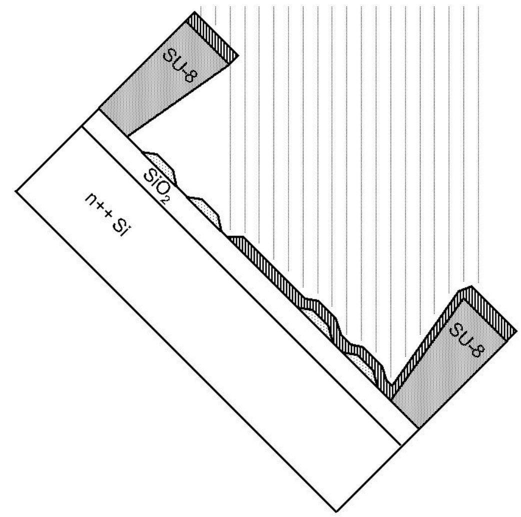

Figure 15.7.2: Schematic cross-section of the complementary device during the n-type semiconductor deposition.

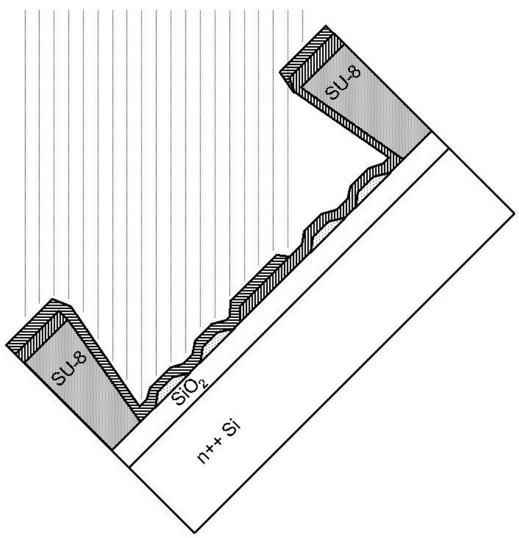

Figure 15.7.3: Schematic cross-section of the complementary device during the p-type semiconductor deposition.

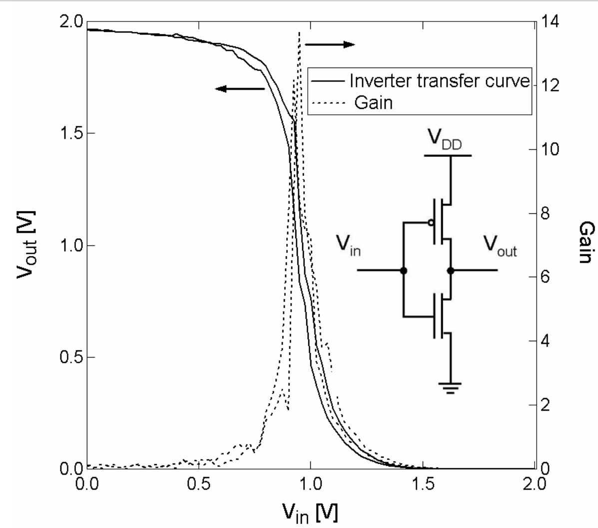

Figure 15.7.4: Measured inverter curve (full curve) and resulting gain (dotted curve) for V_{DD}= 2 V. The inset shows the circuit schematic of a complementary inverter.

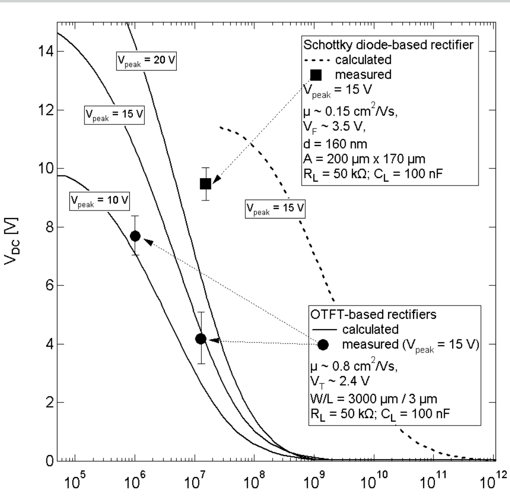

Figure 15.7.5: Experimental and theoretical comparison of OTFT-based and Schottky diode-based rectifiers.

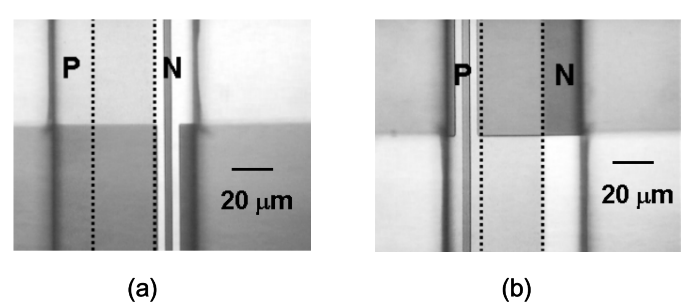

Figure 15.7.6: Optical microscopy images of (a) an n-type OTFT and (b) a p-type OTFT.

Continued on Page 654

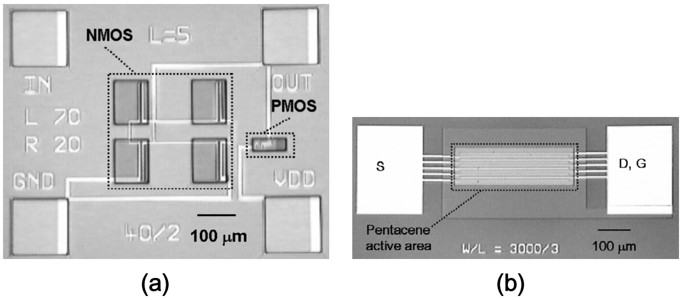

Figure 15.7.7: Micrograph of (a) the complementary inverter and (b) the transistor diode.